RADIATION EMBRITTLEMENT ARCHIVE PROJECT

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ABSTRACT

The Radiation Embrittlement Archive Project (REAP), which is being conducted by the Probabilistic Integrity Safety Assessment (PISA) Program at Oak Ridge National Laboratory under funding from the U.S. Nuclear Regulatory Commission's (NRC) Office of Nuclear Regulatory Research, aims to provide an archival source of information about the effect of neutron radiation on the properties of reactor pressure vessel (RPV) steels. Specifically, this project is an effort to create an Internet-accessible RPV steel embrittlement database.

The project's website, https://reap.ornl.gov, provides information in two forms: (1) a document archive with surveillance capsule(s) reports and related technical reports, in PDF format, for the 104 commercial nuclear power plants (NPPs) in the United States, with similar reports from other countries; and (2) a relational database archive with detailed information extracted from the reports.

The REAP project focuses on data collected from surveillance capsule programs for light-water moderated, nuclear power reactor vessels operated in the United States, including data on Charpy V-notch energy testing results, tensile properties, composition, exposure temperatures, neutron flux (rate of irradiation damage), and fluence, (Fast Neutron Fluence a cumulative measure of irradiation for E>1 MeV). Additionally, REAP contains data from surveillance programs conducted in other countries. REAP is presently being extended to focus on embrittlement data analysis, as well.

This paper summarizes the current status of the REAP database and highlights opportunities to access the data and to participate in the project.

I. INTRODUCTION

Background and Technical Challenges

From the earliest days of commercial nuclear power generation, it was recognized that over time, neutron irradiation hardens and embrittles the steel from which a reactor pressure vessel (RPV) is constructed. Eventually, embrittlement may degrade an RPV's mechanical properties to a point at which the RPV's steel becomes unacceptable from a regulatory perspective, requiring nuclear power plant operators either to make a significant economic investment in replacing or annealing the RPV, or to shut it down. Current regulatory practice for RPV lifetime prediction relies primarily on information gained from Charpy impact testing, tensile testing, and mechanical testing of other small specimens as part of in-reactor surveillance programs. However, this information is limited to the following: a) materials currently in use (by definition, surveillance information is restricted to the types of materials that are in service today), and b) neutron exposures not greatly exceeding the licensed lifetime. Given that the initial

40-year design life of RPVs are now routinely extended to 60 years, the above-stated limitations can produce real restrictions on the operational lifetimes of the nuclear plants.

Neutron embrittlement of RPV steels is known to be a complex phenomenon. The magnitude of embrittlement depends upon the interplay of a number of environmental variables (e.g., fluence, flux, temperature) and compositional ones (that is, the proportions of copper, nickel, manganese, phosphorus, silicon, etc., in the steel). There are considerable amounts of data regarding the effects of neutron embrittlement on both the mechanical properties (e.g., strength, hardness, impact energy, fracture toughness) and the microstructural properties of RPV steels. However, because working on irradiated materials is an expensive undertaking, individual datasets tend to be limited, rarely including complete information on both mechanical and microstructural properties for the same material exposed in both test and power reactors. Both of these factors (i.e., the complexity of the phenomena that create neutron irradiation damage and the lack of comprehensive datasets to quantify its effects) have inhibited progress toward the development and validation of a comprehensive, physically based model sufficiently robust to enable confident prediction of future embrittlement trends.

Motivation and Objective for Construction of REAP Database

It is widely recognized in the field that the NRC regulatory process for RPVs could benefit substantially from a comprehensive, fully electronic, Internet-accessible embrittlement database that would include the following important elements: 1) data entry of past, present and future surveillance capsule reports, and 2) built-in capabilities for calculating the relevant parameters necessary for analyzing the data. In addition, such a database can serve as the foundation for a comprehensive *international* repository of data that would characterize the effects of neutron irradiation embrittlement on the mechanical and microstructural properties of RPV steels; the latter tool could be a crucial element in the NRC's effort to promote the development of a predictive embrittlement model.

In 2010, the NRC responded to the foregoing needs by directing the PISA program to initiate development of the REAP database. The creation of REAP was influenced in part by prior experience with related efforts, summarized as follows:

- Although the NRC requires licensees to submit substantial information regarding the status of materials that constitute the RPV structure [reports on fabrication and testing of specimens contained in in-plant surveillance capsules; see 10 CFR 50 Appendices G and H (2005)], that information is not stored in an easily accessible manner, so its usefulness is limited.

- Because the latter information has not been stored and maintained in a way that facilitates easy assessment, important changes and trends may be difficult to track. An example is changes in embrittlement trend curves as a result of regulatory changes.

- Previous NRC embrittlement database efforts [including Wang (2010) and RVID 2 (2000)] have also been of limited usefulness because they were not continuously maintained or kept up to date. In addition, they were not able to link databases, and they did not link data to the original source documents.

- While existing trend curves provide a consistent prediction of the future for most old materials (e.g., high-copper-containing materials), their ability to predict future characteristics for newer (low-copper) materials is questionable.

This project is necessary because an opportunity is being lost if already existing data are not collected and analyzed with specific reference to embrittlement trends; further, it should be noted that the collection and analysis of already existent specific irradiation data on plants and NPV materials is far less expensive than it is to perform new irradiations.

This project offers the opportunity to collect, verify, and make accessible in one place information that historically was widely dispersed in different databases and under different recovery modes; so it was not, for practical purposes, usable.

Radiation Embrittlement Archive Project (REAP)

As described in the previous section, the NRC commissioned the PISA Program at ORNL to develop a web-based database for US surveillance reports and other data related to embrittlement. With that commission came a proposal that the new database should (as a research tool, not a licensing tool) have the following characteristics:

- Web-based
- able to trace the origin of any information contained in the database
- able to maintain a log of changes of values
- able to reflect and describe what individual data values mean (e.g., how the irradiation temperature is measured)
- able to provide the capability to store documents that show legal permission to make the data and document public
- able to produce information that the NRC can use to post on the data.gov website
- able to define the columns of each table
- able to describe the process of entering data from new citations
- capable of downloading citation data in MS Excel format
- include a feedback form
- able to provide data analysis tools
- searchable

The REAP project provides an important tool for RPV integrity assessment within the NRC regulatory environment, especially as it will constitute a crucial research tool for development of future embrittlement predictive models for light-water-reactor (LWR) RPVs. In addition, the REAP project will assemble disparate data, both un-irradiated and irradiated, from surveillance reports that have been submitted to NRC by the U.S.'s 104 commercial nuclear power plants. Finally, the project will contribute to Reg. Guide 1.99 Rev. 2 (1988) and 10 CFR 50 App. H (2005).

Recognizing that a project of such scope cannot be conducted by any one organization because it requires the participation of organizations and individuals representing a wide range of interests (e.g., regulators, industry, universities, research organizations, and national laboratories) worldwide, the NRC extended invitations to USA and international organizations to participate in a two-day inaugural meeting on September 14-15, 2010, in Rockville, Maryland (USA). The objectives of that meeting were to establish a common appreciation among the participants of the current state of knowledge in embrittlement models and the gaps therein, and to identify a series of next steps that could be taken to develop a participation agreement for data-sharing among interested attendees. The REAP development plan was presented as well.

The REAP database web application was also presented at the International Boiling Water Reactor and Pressurized Water Reactor Materials Reliability Program Conference and Exhibition at National Harbor, MD, from July 16 to 19, 2012. During that event, NRC and the PISA program team presented the REAP project and demonstrated the database's web application in a booth at the conference.

On April 19, 2013, the PISA team prepared and presented a webinar about the current functionality of REAP web application. The REAP webinar recording is available upon request; please see the contacts at the end of this paper.

II. WEB-BASED REAP DATABASE APPLICATION DEVELOPMENT

The remainder of this document focuses on a technical description of REAP from the software engineering point of view.

Sources of REAP Database

REAP's digital archive of source documents includes data for the entire U.S. fleet of 104 commercial nuclear power plants (NPPs) as well as NPP data from other countries. This electronic library contains, in searchable PDF format, the United States' most complete and comprehensive collection of power reactor surveillance reports.

(a) Embrittlement Database Project (EDB)

To compile REAP, the team started with content from the Embrittlement Database Project (EDB), Wang (2010). The EDB database contained power reactor pressure vessel surveillance data, material test reactor data, foreign reactor data (through bilateral agreements authorized by NRC), and fracture toughness data. The EDB effort was sponsored by NRC beginning in 1987 and was designed for use on personal computers using DOS. The data format chosen for EDB was dBASE. The format, initially introduced by Ashton-Tate (2013), was standard in the 1980s and was selected because it allowed queries and data processing not only with dBASE software, but also with other "X-base" developer tools such as Foxpro and MS-ACCESS. Some analysis routines were written in Clipper and FORTRAN.

Quality assurance (QA) of EDB data was handled primarily through the Electric Power Research Institute (EPRI, on a NRC subcontract) with an ORNL interface. EDB Version 1 was released in the middle of 1990 to vendors to verify the accuracy of the data, Wang (2010). The QA checkers included corporate partners such as Westinghouse, General Electric, Babcock & Wilcox and Combustion Engineering.

The QA process basically consisted of the following: 1) comparison of photo copies of tables in the EDB against the hard copies of the surveillance reports; 2) for each data discrepancy found, submission of an EDB Verification Form, a printout of the table with changes marked and initialed by the checker, and a Xerox copy of the referenced pages to approve/reject the change; 3) review and authorization by a Change Control Board to authorize changes to the EDB; 4) execution of authorized changes to the database by the EDB manager at ORNL. All QA documents were archived (however, those documents cannot be located).
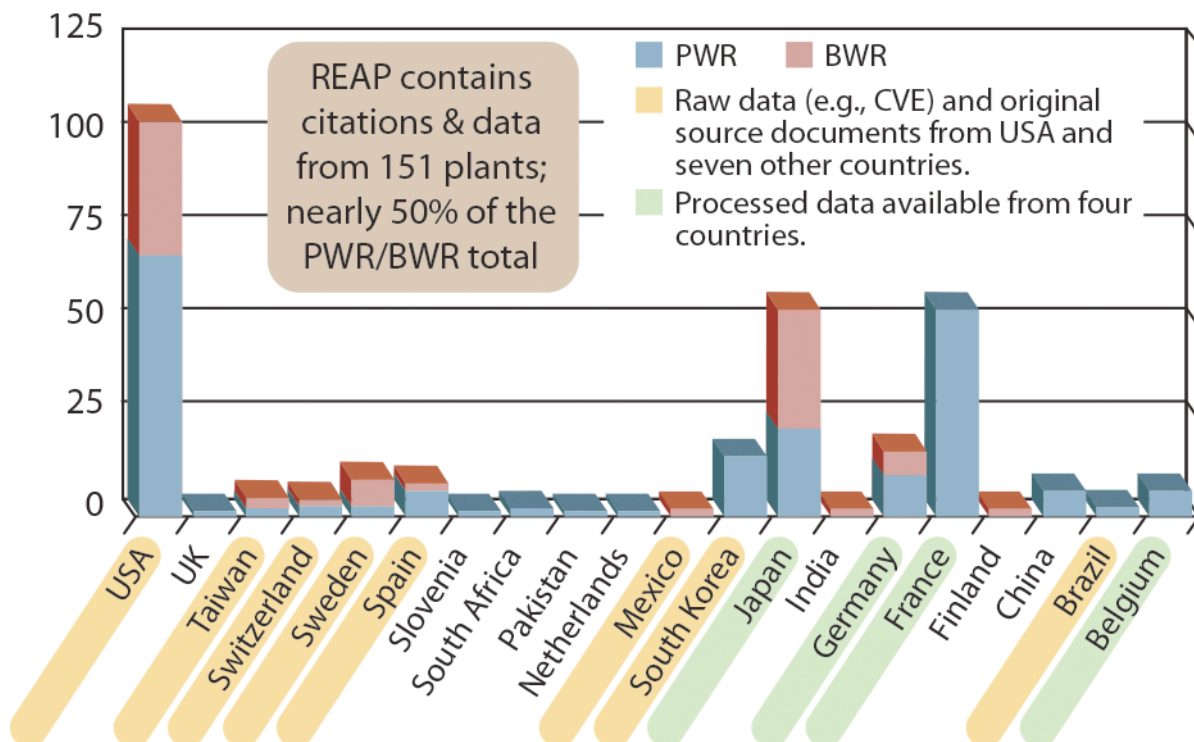

Figure 1. Citations in REAP

(b) Surveillance Capsule Reports and Research Papers

Early in the REAP program, it was recognized that the EDB project had been well documented, but was based on an out-of-date technology. It was also found that data entered into the EDB after March 1991 had not received quality assurance procedures. Furthermore, it was unclear when data input for the EDB had ceased. Fortunately, most supporting documentation, in the form of paper copies, had been held at ORNL facilities and was accessible by the PISA team. That so-called EDB "library" consisted of approximately 160 volumes of reactor surveillance data and supporting documentation, in which reports for individual reactors and summary reports were organized by manufacturer. An unspecified amount of uncatalogued information in assorted boxes had been stored off-site because no on-site storage was available.

Thus, it was necessary to bring all of that information back on site to ORNL to start processing the collected reports. The next step was to convert all hard copies to electronic files. The task included 1) checking reactor reports for completeness and organizations; 2) scanning the reports and putting them into electronically searchable format; and 3) cross-checking the electronic files to assure that all sections had been scanned. This effort took place during 2010 and 2011.

(c) Citations / Data in REAP

Building on a base of U.S. data, the PISA team obtained permission to add raw data (e.g., Charpy V-notch Energy [CVE]) and original source documents from seven other countries (Taiwan, Switzerland, Sweden, Spain, Mexico, South Korea, and Brazil). In addition, some data (e.g., ΔT_{41J}) were processed from four other countries (Japan, Germany, France and Belgium), but without access to the original source documents. Figure 1 shows the citations in REAP by country of origin.

The data contained in REAP are presented as reported in the source documents without additional interpretation. The data include mechanical and embrittlement characteristic information that is needed to perform structural integrity assessments on commercial nuclear RPVs. REAP also contains legal permission to make many of its reports publicly available; the PDF source can be downloaded for those reports that we have legal permission to make public; in cases where we do not have such permission, we do not display the PDF file.

REAP Relational Database Design

Beginning in 2010, the PISA team was able to find a version of the EDB in MS-ACCESS, a fortunate discovery, as the team had no access to the original dBASE system, superseded much earlier. An initial step taken then, was to migrate the EDB in MS-ACCESS version to and industry quality relational database server: the Microsoft SQL Server 2008, R2.

When the PISA team examined the EDB data, we found that working with those data was not a straightforward task. The data input to EDB was highly detailed and complex and was not conceived in terms of relational database principles, so many of the data were duplicated in different fields. In addition, a large number of "orphan" records made it hard to identify their sources. Thus, a major refactoring effort was necessary before the EDB data could be processed.

As a result of those efforts, REAP currently has a relational database with data mined from the reports related to plants, citations, capsules, materials, specimens, chemistry, Charpy and tensile tests for both beginning of life and capsules extracted over time.

The core embrittlement data contained in the REAP database model have been classified within the following groups or tables (see Figure 2):

- Citation: References to the surveillance reports
- Plant: Power reactor nuclear plants
- Capsule: The containment vessel within a nuclear power plant
- Material: Information about the material of which a plant's capsule is made
- Chemistry: Information about the chemical composition of a material

- Heat Treatment: Information about the process of subjecting a material to a cycle of heating and cooling to change the metallurgy of the material.
- Charpy Specimens: Information about a Charpy test that is performed on a material.
- Tensile Specimens: Information about a tensile test that is performed on a material.
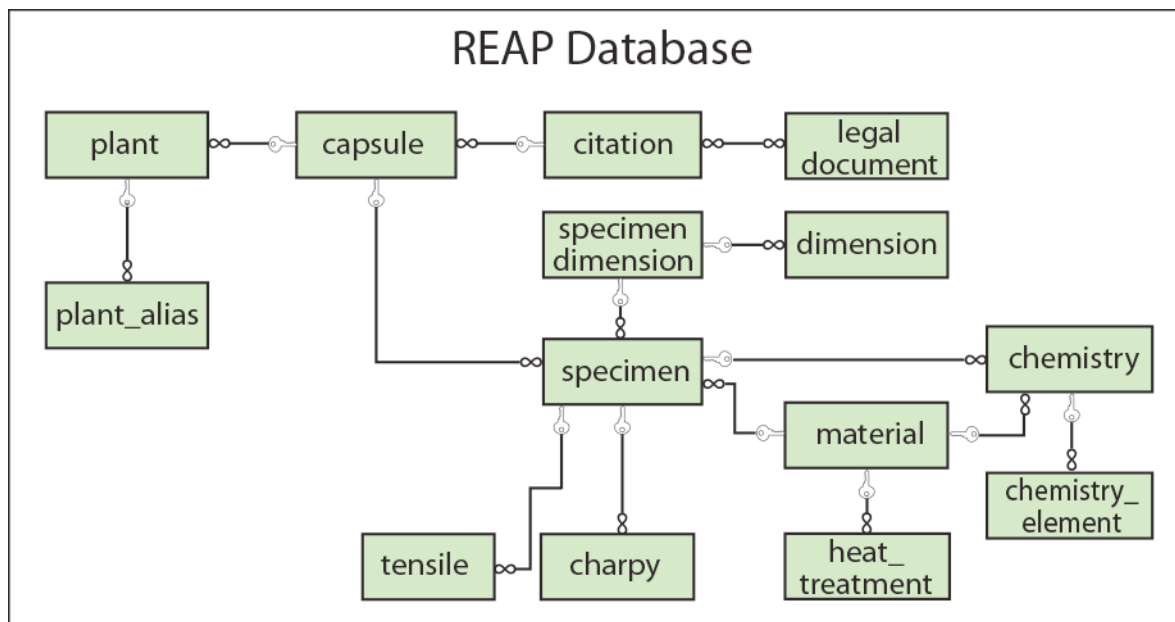

Figure 2. REAP Database Model Design

Figure 2 shows REAP database model design. The categories above are cross-linked or related by identifiers (IDs). For example, in the simplest cases, a citation relates to a power plant, but "citations" could also refer to one or more capsules. Or a citation could describe the beginning of the life of a power plant. "Capsules" contain materials with specific specimen shapes. Parts of the properties of the "materials" are also the "chemistry" properties that are recorded in the chemistry table. These are just a few of the simplest relationships identified and cross-referenced.

REAP Web-Application Architecture

The REAP Web application is being written using a Microsoft ASP.NET MVC 3.0 framework. At the time of writing, REAP web app includes 48,909 lines of code (LOC), using the C# programming language. The Analysis Service Module consists of 5,747 LOC written in C# and 12,436 LOC written in FORTRAN. The relational database system is SQL Server 2008 R2. The development environment and version tracking system are Microsoft Visual Studio 2010 and Team Foundation Server 2010, respectively.

Figure 3 describes the hardware and software architectural design of the REAP Web application. Each block or module depicts a server box. The main components of the system are given as follows:
- The web application server that hosts the production (for final users) and QA (for internal testing) versions of the REAP web application are found at the center of Fig. 3.
- The MS SQL Server boxes, at the sides of Fig. 3, host both the production and the QA versions of the database.
- To access the presented REAP system; users need to obtain ORNL's eXternal Computer Access System (XCAMS) account for authentication.
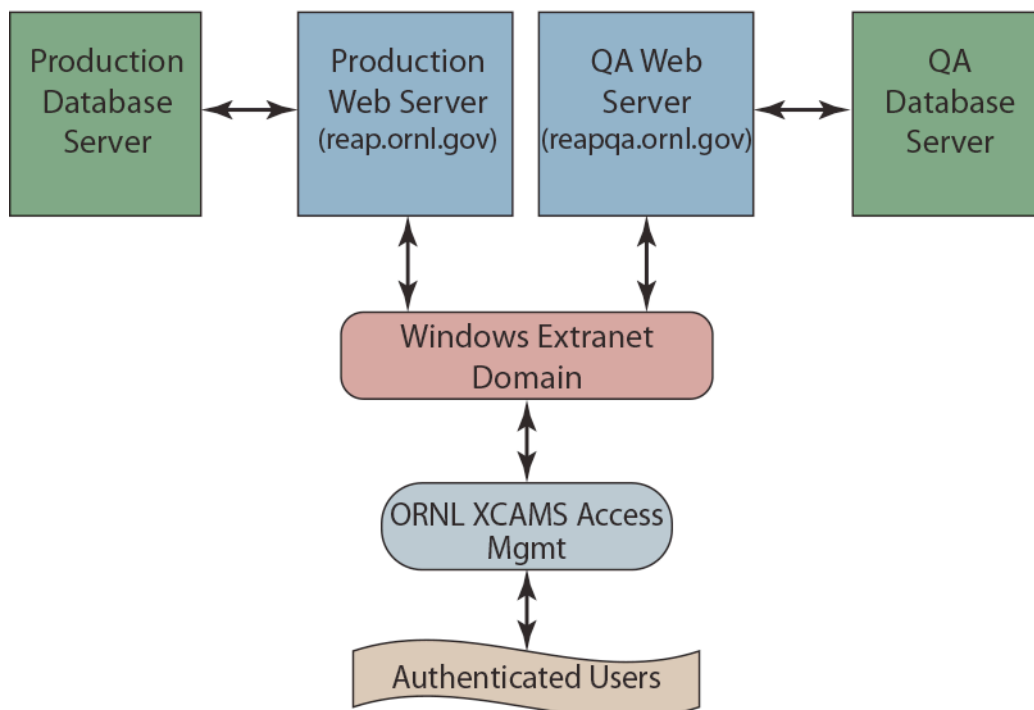
Figure 3. REAP Architecture

REAP Future Plans

The team's efforts focus on the following activities:

- Continuing the development of an Analysis Service Module (ASM) that can perform a Charpy analysis that is depicted in Figure 4. With this functionality, users will be able to run the Charpy analyses directly from the REAP web site without needing to have administrative privileges. The results of their analysis will be stored in a secure area on the user's computer's hard drive. This strategy allows for session state persistence so that users can easily recover the results of previous login sessions. The ASM is being developed using the Microsoft Silverlight Framework (v. 5) Rich Internet Application (RIA), which communicates with the REAP database on the server side through a secure Windows communications foundation (WCF) web service being developed specifically for REAP and employing a service-oriented architecture (SOA) design.
- Developing the user interface to perform complex queries.
- Obtaining remaining surveillance data and source documents.
- Obtaining permissions to post reports/data from more sources.
- Expanding the database to include information from research projects.
- Enabling conversion to other units than the source document ones.
- Allowing for selected analysis of stored data, such as:
  - Average chemistry values, such as transition temperature and shift values; *tanh* fitting of CVE transition curves; master curve fitting to determine To; Zerilli Armstong fitting to determine reference (athermal) yield stress; and other parameters.

- Masking proprietary data to the degree required by the contributor (that is, in some cases just obscuring the reactor that the data came from, or in other cases, obscuring the entire data record)
- Incorporating / reading data from other databases. For example, it is envisioned that later versions of the database will draw upon international sources of data and other research-generated data:
    - Incorporating data from industry-sponsored programs such as those sponsored by EPRI.
    - Incorporating data from RVID 2 (2000)
    - Continuing talks with other countries to participate in the project
    - Including non-U.S. surveillance data from the following sources: Japan, France, Belgium, Spain, and the IAEA Research Reactor Databases (2013)
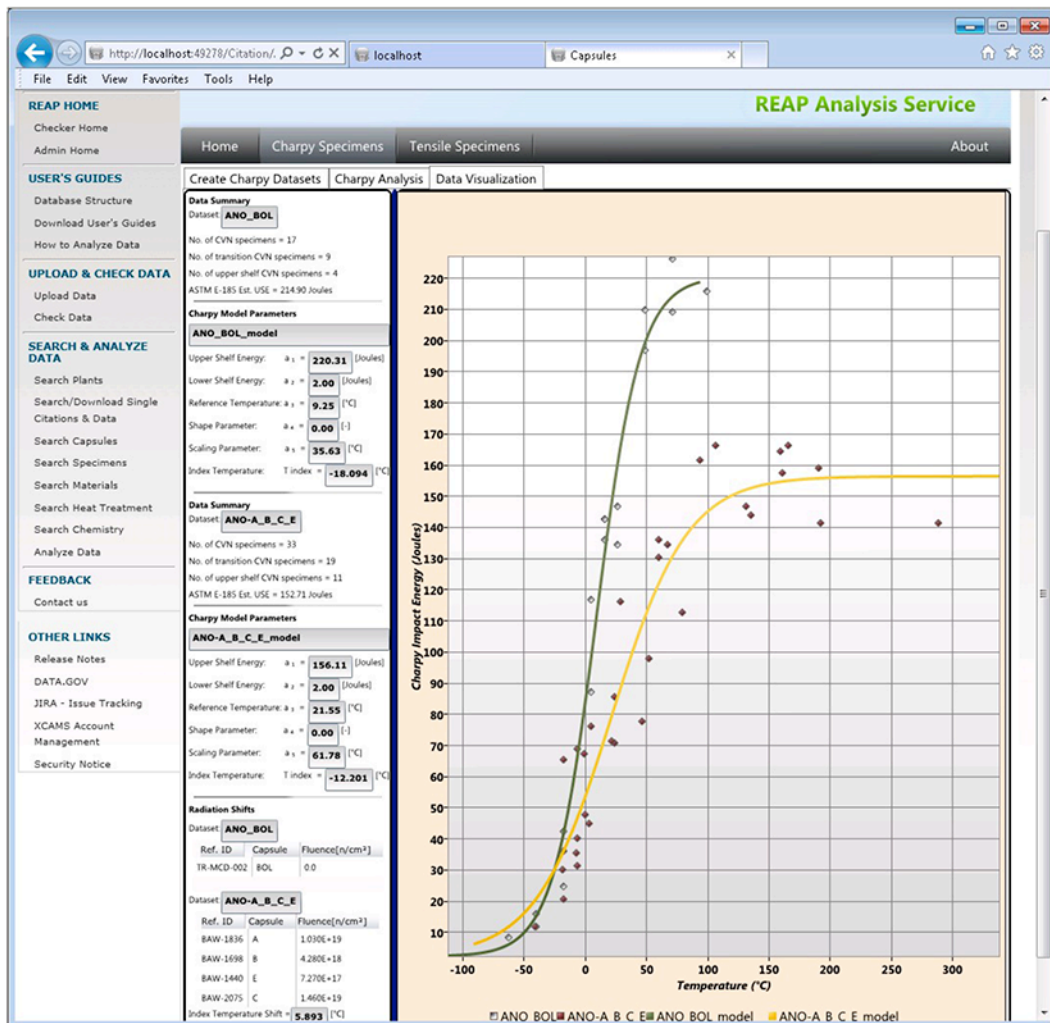

Figure 4. REAP Analysis Service

CONCLUSION

This paper summarizes the current status of the REAP database and highlights opportunities to access the data and to participate in the project.

The project's website, https://reap.ornl.gov, provides information in two forms: (1) a document archive with surveillance capsule(s) reports and related technical reports, in PDF format, for the 104 commercial nuclear power plants (NPPs) in the United States, with similar reports from other countries; and (2) a relational database archive with detailed information extracted from the reports.

REAP focuses on data collected as part of surveillance capsule programs for light-water moderated, nuclear power reactor vessels operated in the United States. This includes data on various tests: Charpy V-notch energy, tensile properties, composition, exposure temperature, flux, and fluence. Additionally, REAP contains some data from surveillance programs conducted in other countries. Work has started on extending REAP to also focus on embrittlement data analysis.

For additional information on topics addressed herein, or to participate in the REAP project, please contact the following:

- Mark Kirk (Mark.Kirk@nrc.gov)
- Gary Stevens (Gary.Stevens@nrc.gov)

Acknowledgments

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